Reference 54-21T

The A. & M. College of Texas

DEPARTMENT OF OCEANOGRAPHY

ON THE SMALLEST SCALE TURBULENCE IN THE ATMOSPHERE

Eiichi Inoue

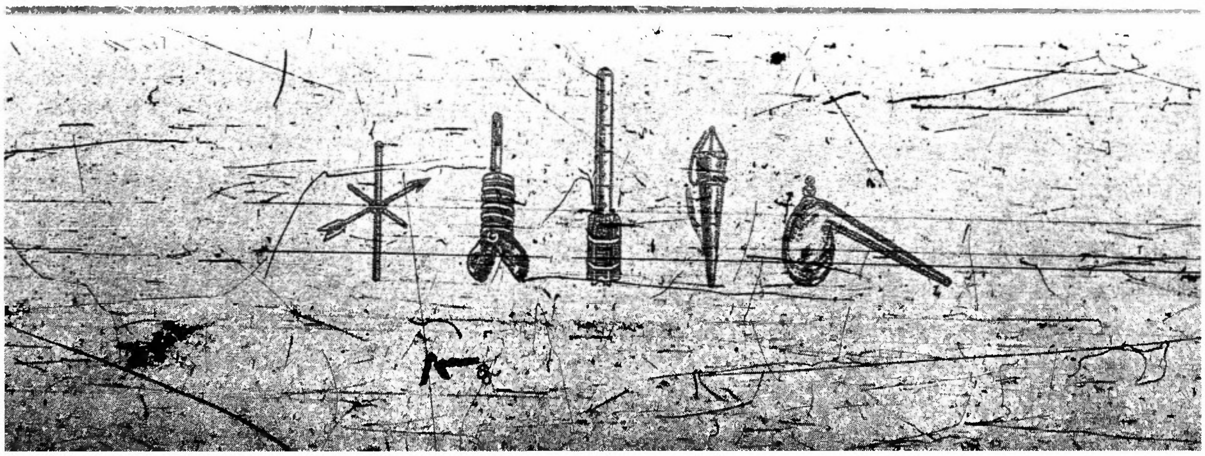
Technical Report No. 1
Office of Naval Research
Contract N7onr-487
Task Order 5
NR 082-011

Scientific Report No. 1
Air Force
Cambridge Research Center
Contract AF19(604)-997

Research Conducted through the

Texas A.&M. Research Foundation

COLLEGE STATION, TEXAS



THE AGRICULTURAL AND MECHANICAL COLLEGE OF TEXAS
Department of Oceanography
College Station, Texas

TEXAS A & M RESEARCH FOUNDATION

Project 59
Technical Report No. 1
Office of Naval Research
Contract N7onr-487
Task Order 5
NR No. 082-111

Project 85
Scientific Report No. 1
Air Force
Cambridge Research Center
Contract AF19(604)-977

ON THE SMALLEST SCALE TURBULENCE IN THE ATMOSPHERE

by

EIICHI INOUE

March 1954

Reference 54-21T

The research reported in this document has been made possible through support and sponsorship extended by the Office of Naval Research under contract N7onr-48705, NR No. 082-111, and by the Geophysics Research Division of the Air Force Cambridge Research Center, Air Research and Development Command, under contract No. AF19(604)-977. It is published for technical information only, and does not necessarily represent recommendations or conclusions of sponsoring agencies.

John C. Freeman, Jr.
Supervisor Project 59

Arnold H. Glaser
Principal Investigator
Project 85

ON THE SMALLEST SCALE TURBULENCE

IN THE ATMOSPHERE

by

EIICHI INOUE

ABSTRACT

This paper deals with the smallest scale of turbulence in any turbulent flow, in particular that in the atmosphere near the ground, to provide guidance in designing instrumentation for measurements of atmospheric turbulence. Discrepancies between G. I. Taylor's "smallest eddy" or "microscale of turbulence" and the concept of "the smallest turbulon" or "internal scale of turbulence", arising from the modern similarity theory of turbulence are pointed out. Physical characteristics of the smallest turbulon in the atmosphere near the ground are studied, and their practical applications discussed.

CONTENTS

ON THE SMALLEST SCALE TURBULENCE

IN THE ATMOSPHERE

by

EIICHI INOUE

1. Introduction

To make successful measurements of turbulence elements, such as turbulent velocity, vorticity, pressure, or temperature fluctuations in the atmosphere, it is obviously necessary to have preliminary estimates of the anticipated characteristics of these elements. Indeed, the choice of instrumentation must largely be governed by such preliminary estimates. In this paper, we will discuss some anticipated characteristics of small scale turbulence in the atmosphere near the ground. This discussion should be of some help in designing instruments for measuring atmospheric turbulence.

The "smallest scale of turbulence" has two distinct definitions which must be discriminated quite clearly. One was first defined by Sir Geoffry Taylor (1935) as "the smallest eddy" of turbulence and is still called "the microscale of turbulence" by many authors, which hardly seems an appropriate designation. The other was first defined by Kolmogoroff (1941) and Obukhoff (1941) as "the scale of the finest pulsation" and now is called "the internal scale of turbulence" by the originators, (Kolmogoroff 1949, Obukhoff and Yaglom 1951) or "the smallest turbulon" by the present author (Inoue 1950).

Though the former has been frequently considered by many authors

(R. J. Taylor 1952, Priestley and Sheppard 1952, Sutton 1953) as the characteristic length of the small eddies which are responsible for viscous dissipation, following Taylor's original speculation, it does not seem a very reasonable interpretation. Indeed, the length of "the smallest eddy" or "the microscale of turbulence" is nothing but a kind of special geometrical mean of the lengths of "the smallest turbulon" and of "the largest turbulon" and is not the length scale of the eddies responsible for most of the dissipation (Inoue 1952b, Batchelor 1953). The concept of "the largest turbulon" clearly corresponds to one of "the mean eddy" defined by Taylor (1935), which is frequently called "the integral scale of turbulence", and is the same one that has been called "the external scale of turbulence", by the originators of the modern similarity theory of turbulence (Obukhoff and Yaglom 1951). In other words, the concept of "the smallest eddy" is nothing but a kind of "mean eddy" and, on the other hand, that of Taylor's "mean eddy" is nothing but "the largest eddy". The aim of the present author in using the special designation of the "turbulon", has been to avoid confusion. Since the length of the characteristic scale of turbulence has been called "the smallest eddy length" and "the mean eddy length", and so on, it seems necessary to make use of such another single designation in order to avoid any possibility of confusion. Indeed, even in some recent papers such confusion has been found, as will be pointed out in this paper.

This problem of terminology has tended to prevent the interchange of knowledge between aerodynamicists, who deal in "microscales" and "smallest eddies", and meteorologists, who talk of "parcels" and "gusts".

2. Relations Between the Smallest Turbulon and Taylor's Smallest Eddy

The idea that in any turbulent flow field there is a certain smallest scale in which the molecular viscosity is predominant and beyond which the turbulent viscosity coefficient is predominant has been proposed by many meteorologists, such as L. F. Richardson (1926) and Kampé de Fériet (1936). The concept of "the smallest turbulon" or "the internal length of turbulence" first proposed by Kolmogoroff (1941) and Obukhoff (1941) seems to the present author as a physical description of this proposed microscale. The scale Λ_∞ and the velocity V_∞ of the smallest turbulon are given by

$$\Lambda_\infty = C_1 \nu^{3/4} \varepsilon^{-1/4} \qquad (2.1)$$

$$V_\infty = C_2 \nu^{1/4} \varepsilon^{1/4} \qquad (2.2)$$

respectively, where ν and ε denote the molecular viscosity of the turbulent fluid medium and the mass rate of turbulence energy dissipation per unit time. The C_1 and C_2, also other C's used hereafter, are all regarded to be universal numerical constants of the order of unity.

On the other hand, the concept of "the smallest eddy" introduced by G. I. Taylor (1935) for a homogeneous and isotropic turbulent flow field, such as wind tunnel flow, also relates ν and ε as follows:

$$\lambda^2 = C_3 \nu \langle u^2 \rangle / \varepsilon, \qquad (2.3)$$

where $\langle u^2 \rangle$ denotes the mean square of the turbulent velocity u and may be regarded as determined by the largest turbulon. That is to say, in the definition Taylor's "smallest eddy" not only the contribution of the

small eddies is considered, but also that of the large eddies, which must be affected by the turbulent viscosity coefficient.

In fact, from the relations (2.1) and (2.3) we can get an interrelation between the smallest turbulon Λ_∞ and the smallest eddy λ as follows:

$$\frac{\lambda^2}{\Lambda_\infty^2} = C_4 \frac{V_0^2}{V_\infty^2} = C_5\left(\frac{\Lambda_0}{\Lambda_\infty}\right)^{2/3} = C_6\left(\frac{K_0}{\nu}\right)^{1/2} \tag{2.4}$$

or

$$\lambda^2 = C_7 \Lambda_0 \Lambda_\infty \left(\frac{\Lambda_\infty}{\Lambda_0}\right)^{1/3}, \tag{2.5}$$

where Λ_0, V_0 and K_0 denote the scale, the velocity, and the diffusion coefficient of the largest or the effectively largest turbulon respectively; they are connected with each other according to the similarity theory of turbulence by the relations:

$$\frac{V_0^3}{\Lambda_0} = \frac{V_\infty^3}{\Lambda_\infty} = C_8\, \varepsilon, \tag{2.6}$$

$$\frac{V_0 \Lambda_0}{K_0} = \frac{V_\infty \Lambda_\infty}{\nu} = C_9 . \tag{2.7}$$

the relation (2.5) implies explicitly that the length λ is a kind of the geometrical mean of Λ_∞ and Λ_0. In other words, the scale of Taylor's smallest eddy denotes a kind of mean length of the internal and the external scale of turbulence, but does by no means denote a measure of the small scale eddies which are responsible for viscous dissipation. Λ_∞ does appear to be the scale of these eddies, and thus, such a designation as "the microscale of turbulence" does not seem to be very

appropriate.* Indeed, in the atmosphere the ratio (K_0/ν) can be as great as 10^{12} or so and λ can be as great as 10^3 cm or so. On the other hand, we can freely choose the scale of phenomena in the atmosphere, as, for example, an observation of wind velocity fluctuations during a relatively short time interval or a mean observation using a short averaging time, in which (K_0/ν) will not be large. In such a case λ can be quite close to Λ_∞, so that Priestley and Sheppard's speculation that the length $(\nu^3/\varepsilon)^{1/4}$ is much smaller than the microscale λ would not necessarily be confirmed. Another interpretation of λ has been given by Lin (1953) as a small scale introduced by space differentiation of the velocity field.

It would appear desirable to call λ "Taylor's dissipation length of turbulence" or something similar, and λ_η, introduced by G. I. Taylor (1953) as another "smallest eddy", "Taylor's diffusion length" or something similar. Then the designation "smallest eddy" might better be applied to Λ_∞ and also Λ_0 might be called the "largest eddy". These suggestions are offered at the risk of still further increasing the confusion of terminology in the hope that better nomenclature may assist in the understanding of the problems of turbulence. Until such a revision of terminology becomes general, the author is forced to use the artificial term "turbulon" in place of "eddy" to avoid confusion.

The concept of the smallest turbulon does not prohibit the existence of velocity fluctuations of scales smaller than Λ_∞, but indicates that

---

*In a wind tunnel flow, where (K_0/ν) is not large, λ is very close to Λ_∞. However, in this case Λ_0 also is close to λ.

such extremely small scale fluctuations are in the regime of laminar motion which does not result in the formation of yet smaller eddies. Some authors (Heisenberg 1948, Inoue 1950) have studied the probable nature of such fine fluctuations, but in order to verify the theoretical considerations experimentally, we must find an instrument which can faithfully follow such fluctuations.

As to the experimental technique of determining the scale Λ_∞, some work has also been done by a few authors (Kolmogoroff 1949, Baranaev at al. 1949, Inoue 1950), but more experimental work seems to be needed.

Problems concerning the experimental determination of Taylor's scales of λ and λ_η have also been considered (Inoue 1952 c, d).

Since the scale Λ_∞ decrease with the increase in ε, at an extremely great value of ε, ca. 10^{17} erg. g^{-1} sec^{-1}, Λ_∞ in the air may tend to the scale of the molecular free path and V_∞ to the molecular velocity. Though this value of ε may be of some interest from the viewpoint of supersonic turbulent flow, no work in this direction seems to have been done. (Inoue 1950).

3. The Smallest Turbulon and the Smallest Eddies in the Atmosphere Near the Ground

From the fairly well verified empirical relation of Richardson (1926),

$$K = 0.2\ L^{4/3}\ cm^2\ sec^{-1}, \tag{3.1}$$

where L is the scale of atmospheric turbulent phenomena measured in cm, we can get a value of Λ_∞ of the order of 1 cm. Of course, this value is of quite a statistical nature, and more detailed information can be obtained from micrometeorological considerations. The quantity ε must

be a complicated function of the height from the ground surface, the surface roughness, the wind velocity, the thermal stability, and so on. When the vertical distribution of mean wind velocity can be expressed by the well-known logarithmic law, which is reasonable under the condition of adiabatic lapse rate, ε may be shown to be in reverse proportion to the height Z, and thus Λ_∞ will be in proportion to $Z^{1/4}$, provided that the change in ν can be neglected. The interrelation between Λ_∞ extremely near the surface and the concept of the laminar boundary sublayer has also been considered (Inoue 1952b).

The concept of Taylor's smallest eddy, or the microscale of turbulence, has been applied to atmospheric turbulence near the ground surface by a few authors. Kawamura (1949) has calculated the Eulerian correlation coefficient making use of the horizontal wind velocity fluctuations obtained with a hot wire anemometer*, and has obtained the value $\lambda = 11.8$ cm applying an osculating parabola to the correlation curve at its vertex. R. J. Taylor (1952) has estimated λ under several conditions with his observation of turbulent energy and the dissipation rate ε, making use of a theoretical relation similar to that of (2.3)**. He finds values from $\lambda = 2$ cm at a height of 2 m to $\lambda = 13$ cm at 30 m (Priestley and Sheppard 1952). To the author, however, it seems that these values must be affected by the change in the averaging time as well as the sensitivity of the measuring instrument and that it is rather difficult to give them much

---

*Platinum wire of 1 cm length and of 0.003 cm diameter was used. The height of measurement was 10 m. The averaging time is not shown.

**The author fears that in his paper R. J. Taylor confused λ and the vertical largest turbulon or the mixing length l.

physical significance.

4. Turbulent Vorticity in the Atmosphere Near the Ground

It is generally supposed that within the inertial range, the smaller the scale of turbulon the greater becomes its vorticity, which is connected with the scale and the velocity as follows:

$$\omega = C_{10}\, \bar{V}/\Lambda$$
$$= C_{11}\, \varepsilon^{1/3} \Lambda^{-2/3} . \qquad (4.1)$$

Thus the vorticity of the smallest turbulon, the scale of which should not be greatly different from that of the smallest turbulon of the inertial range,

$$\omega_{\infty} = C_{12}\, \nu^{-1/2} \varepsilon^{1/2} . \qquad (4.2)$$

The turbulent vorticity should be closely connected with the fluctuations in angular velocity of a swinging wind vane in the atmosphere. It seems natural to suppose that the smaller the wind vane the more violently it should swing. However, detailed observations of this nature have not yet been carried out. In this case, also, the vertical distribution of ε in the atmosphere near the ground may play an important role.

5. Turbulent Pressure Gradients in the Atmosphere Near the Ground

Since the turbulon pressure P is considered to be proportional to ρV^2 statistical characteristics of atmospheric pressure fluctuations may be derived (Batchelor 1953, Inoue 1952b, Obukhoff and Yaglom 1951). Though observations of pressure fluctuations in wind-tunnel flow do not appear to have been made, observations of extremely large scale atmospheric

pressure fluctuations seem to verify the theory (Syono and Gambo 1952). In the medium scale range it may be possible to make such observations by means of an instrument described by Glaser (1952).

Recently Lin (1953) has considered the problem of the observation of pressure fluctuations with an instrument of a certain definite length, or surface, or volume scale, and has discussed some interrelations between the scale of the instrument and the scale of the turbulence. In his discussion, Taylor's microscale of turbulence was used, and here again the term "micro" seems to have caused unnecessary confusion.

The pressure gradient ζ is given formally by

$$\zeta = C_{13} P/\Lambda$$
$$= C_{14} \rho \varepsilon^{2/3} \Lambda^{-1/3}, \qquad (5.1)$$

and has been shown to serve as a coherence force against the disruptive effect of centrifugal accelerations (Inoue 1950). This force is shown to be maximum at the rank of the smallest turbulon, being given by

$$\zeta_\infty = C_{15} \rho \nu^{-1/4} \varepsilon^{3/4}. \qquad (5.2)$$

Some possibilities of measurement exist along the line of the method used and discussed by Kolmogoroff (1949) and Baranaev et al. (1949), who have worked with the disintegration of droplets in turbulent flow.

When the turbulon acceleration ξ is defined by

$$\xi = C_{16} V/\tau, \qquad (5.3)$$

where τ denotes the life-time of a turbulon, being given by $V^2/\varepsilon = C_{17}\Lambda/V = C_{18}\omega^{-1}$, it may be easily seen to be related to the pressure gradient as follows:

$$\xi = C_{19} V^2/\Lambda = C_{20} P/\rho\Lambda$$
$$= C_{21} \zeta/\rho . \qquad (5.4)$$

This quantity is known to be maximum at the smallest turbulon, being given by

$$\zeta_\infty = C_{22}\, \nu^{-1/4}\, \varepsilon^{3/4} . \qquad (5.5)$$

Under logarithmic-law conditions, the quantity ε can be expressed as a function of the mean wind velocity at a fixed point near the ground surface as follows:

$$\varepsilon \backsim U^3(a) . \qquad (5.6)$$

ξ_∞ becomes proportional to the 9/4 power of the mean wind velocity U (a). This characteristic has been pointed out by Obukhoff and Yaglom (1951).

6. Design of the Instrument

The fluctuations in wind velocity which are measured by any wind instrument may be regarded as caused by the action of turbulons carried in the mean wind, and it is obvious that both the geometrical and the temporal characteristics of the instrument have an important influence on the indicated values. For example, any instrument of a scale larger than L may not be able to detect the behavior of turbulons of a scale smaller than L, and thus the results obtained with such an instrument may give rise to false smallest scale corresponding to its own characteristics (Inoue, 1952 b, d).

It is desirable to anticipate the general features of the fine structure of the turbulence before embarking on a program of practical observations.

For experimental work in the wind tunnel flow, some work has been done to determine the effect of the length and the diameter of the hot wire anemometer. In earlier studies, the length λ of Taylor's smallest eddy has been chosen as the characteristic smallest scale; presumable it should be replaced by the length Λ_∞ of the smallest turbulon. However, in general the Reynolds number of turbulence, (Ko/ν), in wind tunnel flow is not large, less than a few hundred, so this confusion of scales may be neglected.

The characteristic smallest period of turbulent fluctuation in wind velocity may be expressed by the passage time T_∞ of the smallest turbulon,

$$T_\infty = \Lambda_\infty / U, \tag{6.1}$$

where U denotes the mean wind velocity carrying the smallest turbulon. In wind tunnel flow T_∞ can be shown in general to be proportional to $U^{-3/2}$. In the atmosphere near the ground T_∞ can be expressed by a function of the height of Z, and mean wind velocity U (a) at a certain height and the roughness parameter Zo of the ground surface as follows:

$$T_\infty(Z) = C_{23}\, \nu^{3/4}\, U^{-7/4}(a)\; Z^{1/4} \left(\log \frac{a}{Z_o}\right)^{7/4} \left(\log \frac{Z}{Z_0}\right)^{-1}. \tag{6.2}$$

Thus, both the scale and the passage time of the smallest turbulon in the atmosphere near the ground are shown to depend upon a number of factors, such as wind velocity and the height from the ground surface, so that the choice of a reasonable combination of length and diameter of a hot wire anemometer, which is to be used for the detection of the smallest turbulon, must also be dependent upon such factors.

For such practical problems in atmospheric turbulence as the turbulent flux of momentum, heat or moisture from the ground surface, the concept of the coupling turbulon which transfers such properties most effectively seems

to be important. The coupling turbulon of which the vertical scale corresponds to the ordinary mixing length has been investigated both theoretically and experimentally (Inoue 1952b, Frankenberger 1952, Shiotani 1953). In order to experimentally detect the behavior of the coupling turbulon the instrument should be sufficiently sensitive both geometrically and temporally. The scale of the coupling turbulon Λ_{0z} is supposed to be $Z \geq \Lambda_{0z} \geq 0.1\,Z$, where Z denotes the height, and thus its passage time may be given by $T_{0z}(Z) = \Lambda_{0z}/U(Z)$, where $\frac{Z}{U(Z)} \geq T_{0z} \geq \frac{0.1\,Z}{U(Z)}$. Observations published by MacCready (1953), in which $Z = 70$ cm and U (70 cm) $= 418$ cm/sec, show that the passage time of the coupling turbulon may range between $0.17 \sim 0.017$ sec. Thus the desirable sensitivity of the instrument may be easily estimated. MacCready points out that under these conditions "about half of the heat flux at 70 cm is transported by eddies with periods under 2 sec."

At the present stage of knowledge of atmospheric turbulence the concept of the smallest turbulon seems of no practical importance, and estimates of its magnitude have been regarded as being merely of theoretical interest. However, this concept may become important in problems of wind erosion and atmospheric pollution, in which the floating, the atomizations, and the coagulation of particles in the atmosphere may be closely connected with the characteristics of the smallest turbulon in the atmosphere. Furthermore, such particles may eventually be used as one of the effective instruments for measurement of the smallest turbulon range in the atmosphere.

7. Conclusion

In reviewing several recent papers by a number of authors in fields

of both meteorology and aerodynamics, the author has tried to make clear the distinction between Taylor's microscale of turbulence or the smallest eddy and Kolmogoroff's internal scale of turbulence or the smallest turbulon. It is pointed out that Taylor's microscale is a kind of geometric mean of the smallest turbulon and the largest turbulon, and that Taylor's microscale can be of the same order as, or greater than the smallest turbulon, depending upon Reynolds number of turbulence. The Reynolds number of turbulence in the atmosphere depends upon many parameters, such as the mean wind velocity, the height, the averaging time, and so on.

In order to carry out effective experimental work in atmospheric turbulence, it seems very desirable to first estimate the interrelations between instrument response and the anticipated characteristics of the smallest turbulon in the atmosphere.

Similar considerations might be applied to the problems of turbulent fluctuations in temperature and humidity, and might be extended to the problems of oceanographic and hydraulic turbulence.

Acknowledgement - I wish to express my sincerest thanks to Dr. Arnold H. Glaser for extended discussion and for his help in putting the manuscript of this paper into acceptable English.

REFERENCES

Baranaev, M. K. et al., 1949: On the magnitude of the minimum pulsations in a turbulent flow, Doklady Akad. Nauk SSSR, 66, 821-24.

Batchelor, G. K., 1953: The theory of homogeneous turbulence, Cambridge, 208 pp.

Frankenberg, E. F. H., 1952: Investigations of the vertical exchange within the lowest decameters at Quickborn, Geophys. Res. Pap. No. 19, 323-343.

Glaser, A. H., 1952: The pitot cylinder as a static pressure prove in turbulent flow, J. Sci. Instru., 29, 219-221.

Heisenberg, W., 1948: Zur statistischen theorie der turbulenz, A. Phys., 124, 628-657.

Inoue, E., 1950: On the smallest turbulon in a turbulent fluid, (in Japanese), Rept. Inst. Sci. Technol., Univ. Tokyo, 4, 194-200.

________ 1952a: On the Lagrangian correlation coefficient for turbulent diffusion and its application to atmospheric diffusion phenomena, Geophys. Res. Pap., No. 19, 397-412.

________ 1952b: On the structure of wind near the ground, (in Japanese), Bull. Nat. Inst. Agric. Sci., Tokyo, A, No. 2, 1-93.

________ 1952c: Some remarks on the Lagrangian correlation coefficient of turbulent diffusion in a wind tunnel flow, J. Phys. Soc. Japan, 7, 503-507.

________ 1952d: Influences of the length of hot-wire anemometer on the measurements of turbulent flow, J. Phys. Soc. Japan, 7, 508-510.

Kampe de Feriet, J., 1936: Atmospheric turbulence, J. Tech. Intern. Aeron., 1936, 431-465.

Kawamura, R., 1949: Experiments on the wind near the ground. (in Japanese), Tech. Rept. Bur. Forestry, No. 1, Tokyo, 65-71.

Kolmogoroff, A. N., 1941: The local structure of turbulence in incompressible viscous fluid for very large Reynolds Numbers, C. R. Acad. Sci. URSS, 30, 301-305.

Kolmogoroff, A. N., 1949: On the disintegration of drops in turbulent flow, Doklady Akad. Nauk SSSR, 66, 825-828.

Lin, C. C., 1953: Note on the mean square value of integrals in the statistical theory of turbulence, Q. Appl. Math., 11, 367-370.

MacCready, P. B., 1953: Structure of atmospheric turbulence, J. Meteor., 10, 434-449.

Obukhoff, A. N., 1941: On the distribution of energy in the spectrum of turbulent flow, Izv. Akad. Nauk SSSR, ser. Geogr. Geofiz., 4, 453. (Translation issued by Min. of Supply, England, as P 21452T).

Obukhoff, A. M. and A. M. Yaglom, 1951: The microstructure of turbulent flow, Prikl. Mat. Mekh., 15, 3-26. (Translation: NACA Tech. Mem. No. 1350, June, 1953).

Priestley, C. H. B. and P. A. Sheppard, 1952: Turbulence and transfer processes in the atmosphere, Q. J. Roy. Meteor. Soc., 78, 488-529.

Richardson, L. F., 1926: Atmospheric diffusion shown on a distance-neighbour graph, Proc. Roy. Soc. A, 110, 709-737.

Shiotani, M., 1953: Some notes on the structure of wind in the lowest layer of the atmosphere, J. Meteor. Soc. Japan, 31, 327-335.

Sutton, O. G., 1953: Micrometeorology, McGraw-Hill, 333 pp.

Syono, S. and K. Gambo, 1952: On numerical prediction (II), J. Meteor. Soc. Japan, 30, 264-271.

Taylor, G. I., 1935: Statistical theory of turbulence, Proc. Roy Soc., A, 151, 421-278.

Taylor, R. J., 1952: The dissipation of kinetic energy in the lowest layers of the atmosphere, Q. J. Roy. Meteor. Soc., 78, 179-185.

Geophysics Branch
Office of Naval Research
Washington 25, D.C.
Attn: Code 416 (2)

Director, Naval Research Laboratory
Washington 25, D.C.
Attn: Technical Information Officer (6)

Officer-in-Charge
Office of Naval Research
London Branch Office
Navy No. 100, Fleet Post Office
New York, New York (2)

Office of Naval Research Branch Office
346 Broadway
New York 13, New York (1)

Office of Naval Research Branch Office
The John Crerar Library Building
86 East Randolph Street, Tenth Floor
Chicago, Illinois (1)

Office of Naval Research Branch Office
1030 East Green Street
Pasadena 1, California (1)

Office of Naval Research Branch Office
1000 Geary Street
San Francisco, California (1)

Office of Technical Services
Department of Commerce
Washington 25, D.C. (1)

Armed Services Tech. Information Center
Documents Service Center
Knott Building
Dayton 2, Ohio (5)

Assistant Secretary of Defense for
Research & Development
Pentagon Building
Washington 25, D.C.
Attn: Com. on Geophysics & Geography (1)

Mr. Francis M. Lucas
ONR Resident Representative
University of Texas
Main Building, Room 2506
Austin 12, Texas (1)

Department of Aerology
U. S. Naval Postgraduate School
Monterey, California (1)

Aerology Branch
Bureau of Aeronautics (Ma-5)
Navy Department
Washington 25, D.C. (1)

Mechanics Division
Naval Research Laboratory
Anacostia Station
Washington 20, D.C.
Attn: J. E. Dinger, Code 3820 (1)

Radio Division I, Code 3420
Naval Research Laboratory
Anacostia Station
Washington 20, D.C. (1)

Meteorology Section
Navy Electronics Laboratory
San Diego 52, California
Attn: L. J. Anderson (1)

Library, Naval Ordnance Laboratory
White Oak
Silver Spring 19, Maryland (1)

Bureau of Ships, Navy Department
Washington 25, D.C.
Attn: Code 851, (Special Devices Center)(1)

Bureau of Ships, Navy Department
Washington 25, D.C.
Attn: Code 327, (Technical Library) (2)

Chief of Naval Operations
Navy Department
Washington 25, D.C.
Attn: Op-533D (2)

Oceanographic Division
U. S. Navy Hydrographic Office
Suitland, Maryland (1)

Library, Naval Ordnance Test Station
Inyokern, China Lake, California (1)

Project AROWA, U. S. Naval Air Station
Building R-48
Norfolk, Virginia (2)

The Chief
Armed Forces Special Weapons Project
P. O. Box 2610
Washington, D.C. (1)

Office of the Chief Signal Officer
Engineering and Technical Service
Washington 25, D.C.
Attn: SIGGGM (1)

Meteorological Branch
Evans Signal Laboratory
Belmar, New Jersey (1)

Office of the Quartermaster General
2nd and T. Sts.
Washington 25, D.C.
Attn: Environmental Protection Section(1)

Commanding Officer
Air Force Cambridge Research Center
230 Albany Street
Cambridge, Massachusetts
Attn: ERHS-1 (1)

Headquarters, Air Weather Service
Andrews A. F. Base
Washington 20, D.C.
Attn: Director Scientific Services (2)

Office of the Chief, Chemical Corps
Research and Engineering Division
Research Branch
Army Chemical Center, Maryland (2)

Commanding General, Air Material Command
Wright Field
Dayton, Ohio
Attn: MCREEO (1)

Commanding General
Air Force Cambridge Research Center
230 Albany Street
Cambridge, Massachusetts
Attn: CRHSL (1)

Commanding General
Air Research & Development Command
P.O. Box 1395
Baltimore 3, Maryland
Attn: RDDG (1)

Department of Meteorology
Massachusetts Institute of Technology
Cambridge, Massachusetts
Attn: H. G. Houghton (1)

Department of Meteorology
University of Chicago
Chicago 37, Illinois
Attn: H. R. Byers (1)

Institute for Advanced Study
Princeton, New Jersey
Attn: J. von Neumann (1)

Scripps Institution of Oceanography
La Jolla, California
Attn: R. Revelle (1)

General Electric Research Laboratory
Schnectady, New York
Attn: I. Langmuir (1)

St. Louis University
3621 Olive Street
St. Louis 8, Missouri
Attn: J. B. Macelwane, SJ. (1)

Department of Meteorology
University of California at Los Angeles
Los Angeles, California
Attn: M. Neiburger (1)

Department of Engineering
University of California at Los Angeles
Los Angeles, California
Attn: L. M. K. Boelter (1)

Department of Meteorology
Florida State University
Tallahassee, Florida
Attn: W. A. Baum (1)

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts
Attn: C. Iselin (1)

The Johns Hopkins University
Department of Civil Engineering
Baltimore, Maryland
Attn: R. Long (1)

The Johns Hopkins University
Department of Physics, Homewood Campus
Baltimore, Maryland
Attn: G. Plass (1)

New Mexico Institute of Mining & Technology
Research and Development Division
Socorro, New Mexico
Attn: E. Workman (1)

University of Chicago
Department of Meteorology
Chicago 37, Illinois
Attn: H. Riehl (1)

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts
Attn: A. Woodcock (1)

General Electric Research Laboratory
Schnectady, New York
Attn: V. Schaefer (1)

Geophysical Institute
University of Alaska
College, Alaska
Attn: C. T. Elvey (1)

Blue Hill Meteorological Observatory
Harvard University
Milton 86, Massachusetts
Attn: C. Brooks (1)

Laboratory of Climatology
Johns Hopkins University
Seabrook, New Jersey (1)

Department of Meteorology
New York University
New York 53, New York
Attn: B. Haurwitz (1)

Massachusetts Institute of Technology
Department of Meteorology
77 Massachusetts Avenue
Cambridge 39, Massachusetts
Attn: T. F. Malone (1)

Rutgers University
College of Agriculture
Department of Meteorology
New Brunswick, New Jersey (1)

National Advisory Committee of Aeronautics
1500 New Hampshire Avenue, N.W.
Washington 25, D.C. (2)

U. S. Weather Bureau
24th & M Sts., N.W.
Washington 25, D.C.
Attn: Scientific Services Division (2)

Air Coordinating Committee
Subcommittee on Aviation Meteorology
Room 2D889-A, The Pentagon
Washington, D.C. (1)

American Meteorological Society
3 Joy Street
Boston 8, Massachusetts
Attn: The Executive Secretary (1)

Research Professor of Aerological Engineering
College of Engineering
Department of Electrical Engineering
University of Florida
Gainesville, Florida (1)

Director of Technical Services
Headquarters, Dugway Proving Grounds
Dugway, Utah (1)

PROJECT 85: Distribution List

Contract AF19(604)-997

5 Armed Services Technical
Information Agency
Documents Services Center
Knott Building
Dayton 2, Ohio

2 Office of Technical Services
Department of Commerce
Washington 25, D. C.

1 Commander
Air Research and Development Command
ATTN: RDDDG
P. O. Box 1395
Baltimore, Maryland

1 Committee on Geophysics and Geography
Research and Development Board
The Pentagon
Washington 25, D. C.

1 Commander
Wright Air Development Center
ATTN: WCACD
Wright-Patterson Air Force Base, Ohio

1 Dr. Athelstan Spilhaus
Institute of Technology
University of Minnesota
Minneapolis, Minnesota

1 Dr. John D. Strong
Johns Hopkins University
Baltimore 18, Marylond

1 Dr. Harry Wexler
Chief, Scientific Services Division
U. S. Weather Bureau
24th and M Streets, NW
Washington 25, D. C.

1 Project AROWA
Naval Air Station, Bldg R-48
Norfolk, Virginia

1 Office of Naval Research
ATTN: Geophysics Code N-416
Washington 25, D. C.

1 Library
U. S. Weather Bureau
24th and M Streets, N W
Washington 25, D. C.

1 Chief, U. S. Weather Bureau
ATTN: Scientific Services Division
24th and M Streets, N W
Washington 25, D. C.

1 Air Coordinating Committee
Subcom. on Aviation Meteorology
The Pentagon
Washington 25, D. C.

1 National Advisory Committee for
Aeronautics
Subcom. on Meteorological Problems
1724 F Street, N W
Washington 25, D. C.

1 Librarian
Sandia Corporation
Sandia Base
Albuquerque, New Mexico

1 Dr. Fred L. Whipple
Harvard College Observatory
60 Garden Street
Cambridge, Massachusetts

1 Dr. Joseph Kaplan
Department of Physics
University of California
Los Angeles, California

1 Director
Air University Library
ATTN: CR 4582
Maxwell Air Force Base, Alabama

2 Commander
Air Weather Service
ATTN: DSS, Tech. Info. Branch
Andrews Air Force Base
Washington 25, D. C.

1 Project Black Sheep
P. O. Box 6225
McDill Air Force Base
Tampa, Florida

1 Office of the Chief Signal Officer
Eng. and Tech. Division
ATTN: SIGGEE-A
The Pentagon
Washington 25, D. C.

1 Commanding Officer
Evans Signal Laboratory
ATTN: Chief, Meteorological Branch
Belmar, New Jersey

2 Director
Naval Research Laboratory
ATTN: Code 2021
Washington 25, D. C.

1 Department of Meteorology
New York University
University Heights
New York 53, New York

1 Chairman, Dept. of Meteorology
Massachusetts Institute of Technology
Cambridge 39, Massachusétts

1 Department of Meteorology
University of Chicago
Chicago, Illinois

1 Laboratory of Climatology
Johns Hopkins University
Seabrook, New Jersey

1 Department of Meteorology
University of California
Los Angeles, California

1 Director, Geophysical Observatory
University of Alaska
College, Alaska

1 Dr. V. H. Regener
University of New Mexico
Albuquerque, New Mexico

1 Librarian, Technical Library
Dugway Proving Ground
Tooele, Utah

1 Meteorological Office
Department of Transport
315 Bloor Street
Toronto 5, Ontario, Canada

1 American Meteorological Society
P. O. Box 1736
ATTN: Malcolm Rigby
Washington 13, D. C.

1 American Meteorological Society
Office of the Executive Secretary
3 Joy Street
Boston 8, Massachusetts

1 Commander
Holloman Air Development
ATTN: HDOT
Holloman Air Force Base
New Mexico

1 Chief of Naval Operations
ATTN: Aerology Branch
The Pentagon
Washington 25, D. C.

1 The Rand Corporation
1500 Fourth Street
Santa Monica, California

1 Civil Engineering Department
The Johns Hopkins University
Baltimore 18, Maryland

20 Commander
Air Force Cambridge Research Center
ATTN: CRAMT (GRD Int. Dist.)
230 Albany Street
Cambridge 39, Massachusetts

1 The John Crerar Library
Science-Technology-Medicine
86 East Randolph Street
Chicago, Illinois